Scientific note

Arctic experiment for ICESat/GLAS ground validation with a Micro-Pulse Lidar at Ny-Ålesund, Svalbard

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Abstract: A Micro-Pulse Lidar (MPL) has been operated in Ny-Ålesund, Svalbard (78°55′N, 11°56′E, 0.010 km msl) to collect zenith scattering profiles of aerosols and clouds since 1998. The Ice, Cloud, and land Elevation Satellite (ICESat) was launched by NASA in January 2003 with a single payload instrument, the Geoscience Laser Altimeter System (GLAS), designed for active remote sensing of the atmosphere as well as ice sheet height change in the cryosphere. Overpass experiments for ground validation of the ICESat/GLAS atmospheric measurements were performed in 2003 and 2004. Two case-studies comparing lidar measurements from space-borne GLAS and ground-based MPL in the Arctic are described here for a geometrically thick but optically thin cloud and a geo-metrically thin but optically thick cloud. The result validates the basic procedure for cloud signal processing and attenuation correction of the GLAS data.

key words: Arctic, cloud, Micro-Pulse Lidar, Geoscience Laser Altimeter System

1. Introduction

It is generally recognized that clouds and aerosols have important roles in the global climate system due to their radiative effects on the planetary radiation budget. The distribu-tion and optical properties of clouds and aerosols are essential for quantitatively estimating direct atmospheric radiative forcing. Remote sensing is a good and widely used technique to derive the physical and optical properties of clouds and aerosols. Furthermore, active remote sensing instruments such as lidars and radars are more robust than passive instru-ments, and are now becoming popular not only for ground-based but also space-based applications. The Geoscience Laser Altimeter System (GLAS) was launched aboard the Ice, Cloud and Land Elevation Satellite (ICESat) in January 2003. The mission focus is on con-

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tinuous measurements of the atmosphere, ice sheets and land (Zwally *et al*., 2002). Space-borne lidar observations by ICESat/GLAS provide global coverage of vertical profiles of clouds and aerosols, including both polar regions since GLAS is the first polar-orbiting satellite lidar instrument (Spinhirne and Palm, 1996; Spinhirne *et al*., 2005a). Several results from recent GLAS measurements have been reported (*e.g*., Mahesh *et al*., 2004; Hart *et al*., 2005; Hlavka *et al*., 2005; Palm *et al*., 2005; Spinhirne *et al*., 2005b). Ground calibration/validation experiments are essential for quantitative evaluation of satellite retrieval algorithms. The Micro-Pulse Lidar Network (MPLNET) is a world-wide network of ground-based Micro-Pulse Lidar (MPL) measurements organized and managed by NASA Goddard Space Flight Center (Welton *et al*., 2002). The MPLNET sites are included in the GLAS calibration/validation initiative to contribute to GLAS validation exercises.

Science data products from the space borne lidar include the detection and height distribution of cloud layers. There are two main advantages of lidar sensing of cloud over passive sensors. One is of course the direct and unambiguous measurement of height distribution. A second is the high sensitivity to detect cloud scattering over any surface if the lidar system is operating correctly. A goal for the space lidar data is to detect all clouds including multiple layers. A complexity is the attenuation of the scattered signal with propagation that the data algorithms attempt to correct for through several optical thicknesses. Important issues to verify for the global cloud data products are the sensitivity of detection of thinnest cloud layers, the optical depth through which lower cloud layers can be detected and the related issue of how well and to what degree the data processing algorithms function to correct for attenuation within clouds. The validation program for the GLAS experiment thus included direct comparison to surface measurements, both lidars and photometers. The satellite bus for GLAS includes the ability to point directly to surface sites to an accuracy of 30 m on the ground when the sites are within five degrees of the orbit nadir track. Thus direct one-to-one comparisons are possible. When GLAS is operating, at approximately one site, using primarily photometers but also lidars, each orbit is targeted. The only Arctic lidar site was Ny-Ålesund, Svalbard.

The National Institute of Polar Research (NIPR) promotes atmospheric research in both Arctic and Antarctic regions. Intended for long-term monitoring of the vertical structure and optical properties of clouds and aerosols in the Polar Regions, NIPR is operating MPLs at Ny-Ålesund, Svalbard in the Arctic and at Syowa Station, Antarctica (Shiobara *et al*., 2003). Both sites belong to MPLNET and have participated in GLAS calibration/validation activities. Arctic MPL measurements have been made since 1998, including GLAS overpass experiment periods in 2003 and 2004. Simultaneous measurements of cloud and aerosol from MPL and GLAS were successfully performed in these periods for six overpasses above Ny-Ålesund. In this paper, MPL measurements are described as ground truth for ICESat/GLAS cloud and aerosol measurements during overpass opportunities in fall 2003.

2. Measurements

The Micro-Pulse Lidar (MPL) is a portable laser radar system designed to collect long-term datasets of cloud and aerosol backscatter profiles (Spinhirne, 1993). In order to monitor the vertical structure and optical properties of clouds and aerosols in the polar regions, MPL measurements began at Ny-Ålesund, Svalbard in the Arctic in 1998. A prototype

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MPL system manufactured by Science Engineering Systems Inc., USA was originally operated at the NIPR Rabben Observatory (Shiobara *et al.*, 2003). An upgraded instrument, featuring new optics and detector assemblies, was installed in 2002. In June 2003, the MPL was relocated to the NDSC building of Koldewey Station (78°55′N, 11°56′E, 0.010 km msl). This facility was reorganized to be part of the joint French-German Arctic Research Base in 2003, and has been managed by the Alfred Wegener Institute for Polar and Marine Research (AWI). Since then the MPL telescope has been pointed to zenith through a roof window for vertical measurements (see Fig. 1). The MPL measurement is fully automated. The measurement wavelength is 0.523 μm. Data are acquired with a 0.030-km range resolution up to 60.0 km high on a 24-hour operation basis and averaged for each one minute. Data are transferred daily to the MPLNET data server and processed to provide corrected backscatter profiles (Campbell *et al.*, 2002; Welton and Campbell, 2002). For data normalization, calibration measurements of afterpulse and dark counts are acquired bi-monthly by the AWI on-site technical staff. Processed data are available from the MPLNET website at http://mplnet.gsfc.nasa.gov/.

ICESat is a near-polar orbiting satellite with an orbit inclination of 94 degrees, flying with a speed of 7.2 km/s at a nominal altitude of 600.0 km. A complete orbit cycle takes approximately 100 min. GLAS is the lone sensor on the ICESat platform. The near-polar orbital track provides global coverage of vertical profiles of cloud and aerosol including both polar regions. GLAS is equipped with a Nd:YAG laser and has two channels of 0.532 and 1.064 μm. The GLAS laser pulses at 40 Hz. When pointing toward the nadir the laser
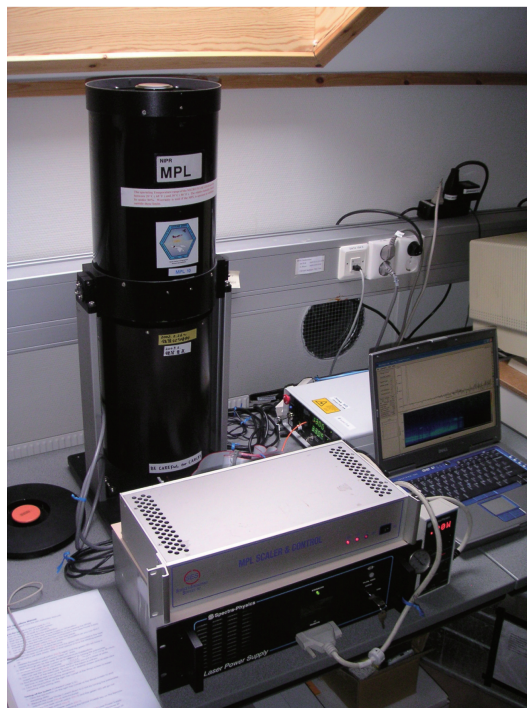

Fig. 1. A NASA-upgraded SESI MPL system placed at the NDSC building of the German Koldewey Station in Ny-Ålesund, Svalbard.

spot strikes the planet surface at nominal 0.172 km intervals along the flight track, with a footprint diameter close to 0.070 km. The fundamental vertical resolution for the atmospheric measurement is 0.076 km. Data products include optical depths of thin cloud and aerosol at both wavelengths (Palm *et al*., 2002; Spinhirne *et al*., 2005a).

GLAS data validation issues involve the sensitivity of cloud detection and optical depth retrieval accuracy. GLAS measurements and retrieval algorithms are designed to obtain cloud and aerosol optical depths ranging from 0.01 to 2.0, with an accuracy of 30% (Spinhirne and Palm, 1996; Zwally *et al*., 2002). Precise examinations of GLAS data have indicated that the lowest sensitivity of the cloud optical depth (COD) in the 0.532 μm channel is actually between 0.001 and 0.02 depending on background and geometric thickness (Spinhirne *et al*., 2005a).

For ground-truth validation of the GLAS cloud and aerosol measurements ICESat overpass opportunities were coordinated in October–November 2003, February–March 2004 and May–June 2004. ICESat was pointed directly to the Ny-Ålesund site when within five degrees of nadir by the attitude control system. Simultaneous data from MPL and GLAS were obtained for six overpasses at Ny-Ålesund during the October–November 2003 period. Exact date, time and atmospheric conditions for each overpass experiment are summarized in Table 1.

Table 1.   ICESat/GLAS overpass experiment for Ny-Ålesund site.

| Date	Time	General description of cloud properties
1. 2003/10/16,	1733	Geometrically thin but optically thick low cloud
2. 2003/10/26,	0800	Low and thick cloud
3. 2003/11/02,	1706	Geometrically thick but optically thin high cloud
4. 2003/11/10,	1648	Geometrically/optically thick cloud
5. 2003/11/12,	0733	Low cloud with snow precipitation
6. 2003/11/20,	0714	Geometrically thin but optically thick low cloud
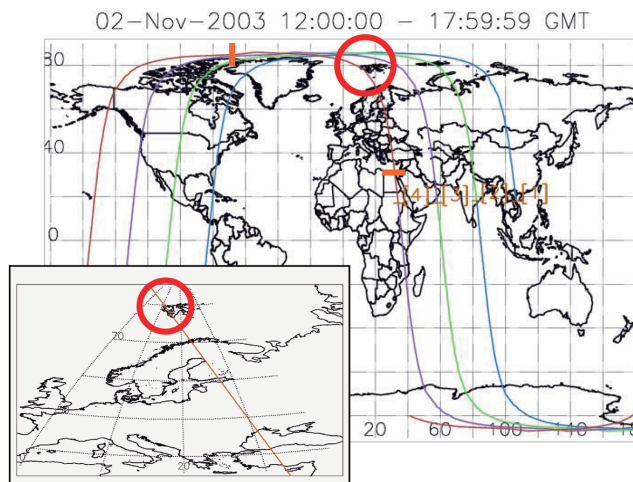
Fig. 2.   The GLAS space flight tracks for 1200–1800 GMT on 2 November 2003, including an overpass flight above Ny-Ålesund (red circles).
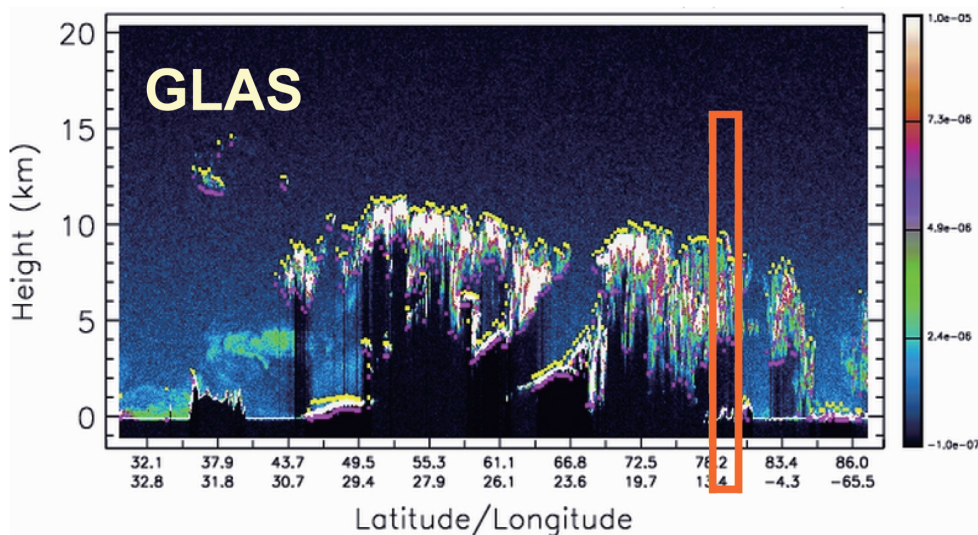
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Fig. 3. *The GLAS-measured attenuated backscatter cross section profiles from the ICESat Global Backscatter Data Product (GLA07) and cloud height from the Global Cloud Heights for Multi-layered Clouds Product (GLA09), along the track between the two bold orange bars in Fig. 2. The GLAS overpass measurement just above the Ny-Ålesund site is indicated by the orange rectangle that is expanded for the profile in Fig. 5.*

Figure 2 is an example of the ICESat orbital tracks for six hours on 2 November 2003, 1200–1800 GMT including 4 legs indicated by multi-colored lines; starting north of Vietnam with the blue line, followed by green, purple and brown lines ending in Antarctica. Each orbit shifts the flight track westward. Ground tracks were repeated every eight days during the calibration/validation phase of the ICESat/GLAS mission. Figure 3 shows the time-series of 0.532 μm attenuated backscatter cross section ($m^{-1}sr^{-1}$) profiles for the 6900 km track denoted between the two bold orange bars on the brown flight track in Fig. 2. The time-series profile includes cloud, land and ocean targets occurring from north of Africa and Greenland *via* Europe from 1653–1709 GMT. An ICESat overpass above the Ny-Ålesund MPL site occurs at 17:06:16 GMT, and is denoted by red circles in Fig. 2. The GLAS measurement just above Ny-Ålesund is indicated by the orange rectangle in Fig. 3. Details of this overpass measurement are shown in the following section.

3. Results and discussion

Arctic MPL measurements coincided with the period of the GLAS overpass/validation experiments in 2003 and 2004. Results from the concurrent Arctic MPL-GLAS measurements are shown and discussed here. One of the purposes of the overpass experiment is direct comparisons of cloud and aerosol profiles, and retrievals such as extinction coefficient profiles and optical depths. In this paper we focus on two cases; geometrically thick but optically thin cloud and geometrically thin but optically thick cloud. For both cases, lidar profiles and cloud optical depths (CODs) from space-borne GLAS and ground-based MPL measurements are compared and discussed to evaluate their performances.

3.1. Geometrically thick but optically thin high cloud: 2 November 2003

Figure 4 shows one-minute averaged normalized relative backscatter (NRB; Campbell *et al.*, 2002) profiles from the MPL at Ny-Ålesund for 24 hours of measurements on 2 November 2003 (306th day of year). High cloud apparent in the morning becomes thicker with time over the course of the day, eventually being observed from 4.0–10.0 km. One-second averaged attenuated backscatter profiles from GLAS for 17:06:05–17:06:28 GMT on the same day are shown in Fig. 5 for the overpass experiment above the Ny-Ålesund MPL site. The exact overpass time was 17:06:16 GMT, as indicated by the orange rectangle in Figs. 4 and 5. The data show that the lasers from both the MPL and GLAS instruments penetrated the cloud layer. From Fig. 5 a "ground-return stroke" is evident meaning that the GLAS laser pulse has reached the ground (or sea) surface. As a result the cloud top and bottom were both sampled, as shown by dashed lines in Fig. 6. Also the fine structure of the cloud layer is coincidently profiled by both the MPL and GLAS measurements. This means that the same cloud was successfully observed from both space and ground. It should be noted, however, that the profiles are not for exactly the same cloud volume due to the sampling differences of one being instantaneous over about seven kilometers and the other a temporal average at one point, and the comparison is thus subject to cloud inhomogeneity. But the data are for the same close location. It can be seen that the GLAS profile in Fig. 6, which includes the attenuation correction for the backscatter cross section, has cross section values ranging near 10^{-2} km^{-1}sr^{-1}. The GLAS optical thickness retrieval for the cloud region is in the range of 1.2, which corresponds to an attenuation correction greater than a factor of three. It is seen that the MPL cross section for the lower cloud region, though larger, is within 20%. For the top of the cloud, the comparison shows a MPL cross section some 50% lower. However, the cloud inhomogeneity appears greater for the upper cloud
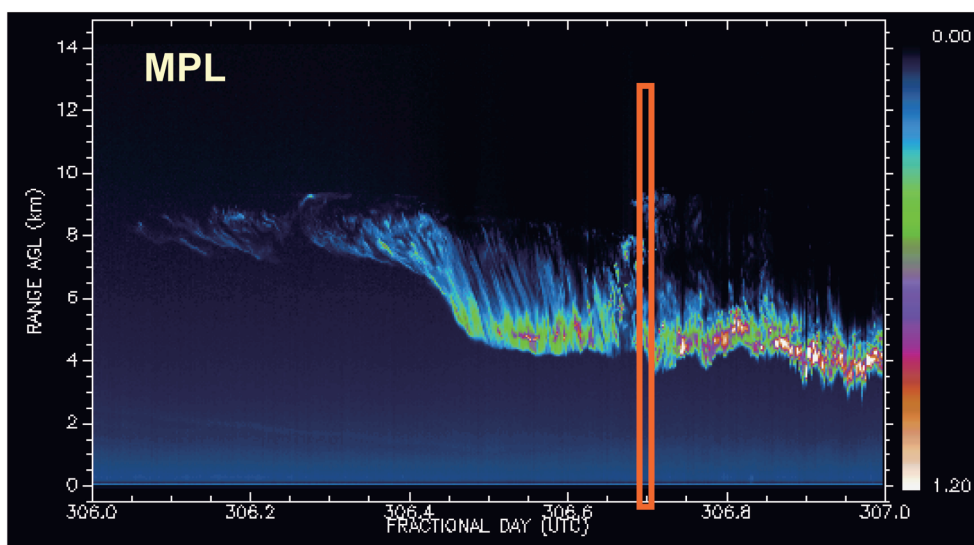

Fig. 4. The height-time color map of the normalized relative backscatter (counts·km^2 $\mu J^{-1}\mu s^{-1}$) profile measured by MPL at Ny-Ålesund on 2 November 2003. The measurements within the orange rectangle correspond to the GLAS measurements in Fig. 5.
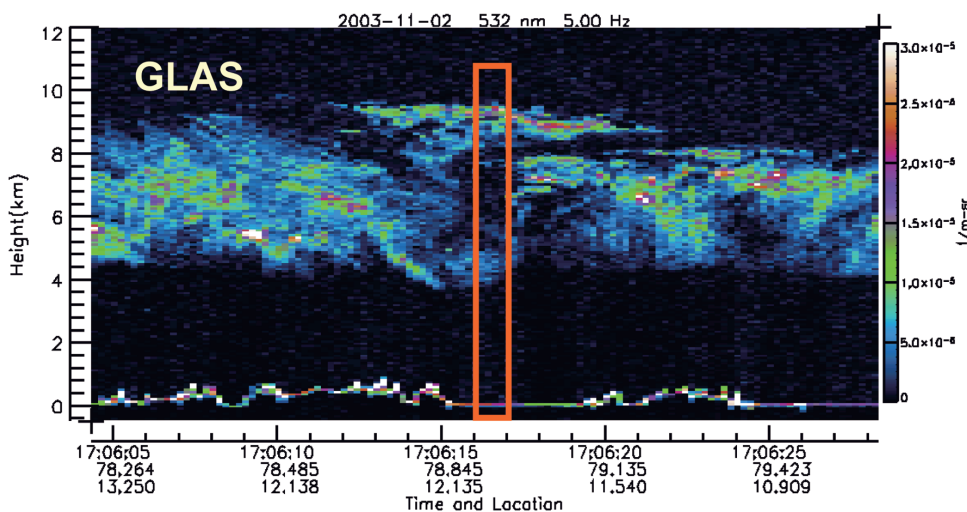
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Fig. 5. *The height-time color map of attenuated backscatter cross section at 0.532 μm measured by GLAS during the overpass flight above Ny-Ålesund on 2 November 2003. The orange rectangle corresponds to the averaged profile in Fig. 6 to compare with the MPL profile for ground validation.*
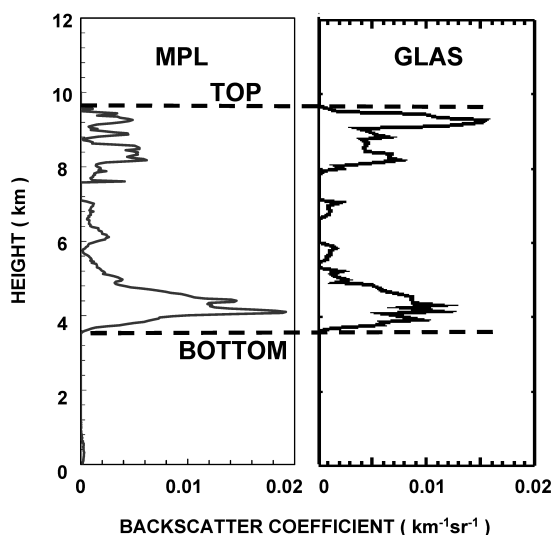

Fig. 6. *Vertical profiles of the corrected backscatter coefficient obtained from MPL (left) and from GLAS (right), respectively, on 2 November 2003 for an example of the geometrically thick but optically thin case. Top and bottom heights of the cloud layer are indicated by dashed lines.*

and thus much more likely to be in error due to sampling. In addition, as described below, the MPL attenuation correction will be more uncertain. MPL retrievals for extinction and backscatter coefficients are described by Campbell *et al.* (2003) and Welton *et al.* (2000).

Overall the comparison, within the bounds of expected sampling inhomogeneity, gives confidence in the basic correctness of the GLAS signal attenuation correction and thus also the optical depth retrieval for a fairly thick cloud layer.

CODs from MPL and GLAS are independently obtained and compared. The MPL-retrieved COD was about 0.4 at the overpass time (orange rectangle in Fig. 4), while the GLAS retrieved COD was changing from 1.5 to 1.0 at the time corresponding to the rectangle in Fig. 5. This shows the difficulty of direct comparison of CODs for variable cloud layers. A possible reason of the discrepancy could be due to multiple scattering. The lidar algorithms first obtain the effective optical depth. For GLAS data, multiple scattering reduces the effective optical depth relative to the actual optical depth in the range of a factor of two. There is no such reduction for the MPL due to the greatly small range and beam footprint, and thus the attenuation correction is larger and hence more uncertain. Another factor is the treatment of S-ratio for clouds (*i.e.*, the extinction to backscatter ratio; a key parameter for inverting elastic single-channel backscatter profiles due to the presence of two unknowns in the singular lidar equation). In the MPL analysis, the S-ratio was assumed to be 20 sr for ice clouds. On the other hand, the GLAS analysis employs a layer temperature based parameterization of the scattering ratio for cirrus clouds and higher values of S-ratio around 30 sr. As a result, COD values from GLAS are likely larger than those from MPL. As stated above, the good agreement of the cross sections for the lower cloud provides confidence in the GLAS derived COD. Since the S-ratio depends on the scattering phase function and thus on the particle radius and shape, a proper value of the S-ratio should be assumed for each cloud type. In the present case we cannot rule out the presence of liquid water droplets near the cloud base, which would further complicate the basic MPL retrievals in this case and possible magnify error due to any spatial sampling differences present between the two instruments. Only a few hours later the MPL experienced total laser attenuation from relatively strong scattering in the first two kilometers of the cloud (Fig. 4). Application of the S-ratio for various water and ice clouds in order to estimate COD more accurately requires further study, both for GLAS and the recently launched CALIPSO satellite lidar instrument (Vaughan *et al*., 2004).

3.2. *Geometrically thin but optically thick low cloud: 16 October 2003*

Figure 7 is the MPL NRB profile from 16 October 2003. The figure shows that there has been precipitation from thick low clouds in the morning, though it ceased by around 1600 GMT. An attenuating cloud then appeared at 2.0 km. Total attenuation of the MPL laser pulse occurred over only a short range here, likely indicating a composition dominated by liquid water droplets. However, the cloud was glaciating. Weakly scattering elements can be seen below the cloud base. These are most likely ice virga, a common characteristic of mixed-phase altocumulus clouds (*e.g*., Wang *et al*., 2004). Higher clouds are apparent from breaks in the lower cloud near 4.0 km. For comparison with the MPL profile, a one-second averaged attenuated backscatter profile from GLAS for 17:33:21–17:33:28 is illustrated in Fig. 8. The exact overpass time for this experiment was 17:33:24 GMT, as denoted by the orange rectangle in Figs. 7 and 8. Since the cloud at about 2.0 km was geometrically thin but optically thick, the lasers from both MPL and GLAS did not penetrate the cloud layer at the overpass time. No "ground-stroke" is visible in Fig. 8 to indicate penetration of the GLAS laser through the cloud. The cloud was too thick to retrieve the corrected
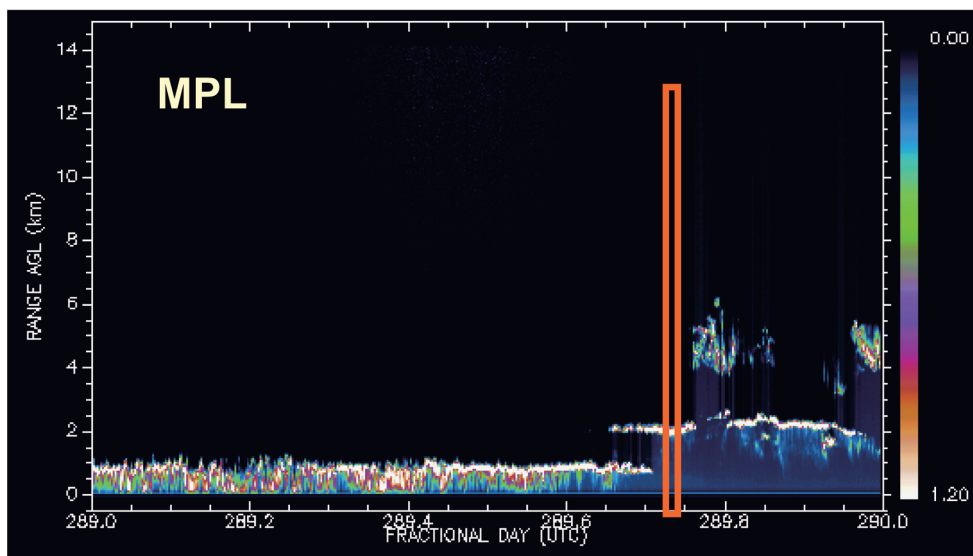
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Fig. 7. *The height-time color map of normalized relative backscatter (counts·km^2 $\mu J^{-1} \mu s^{-1}$) pro-*
file measured by MPL at Ny-Ålesund on 16 October 2003. The measurements within the
orange rectangle correspond to the GLAS overpass measurements in Fig. 8.
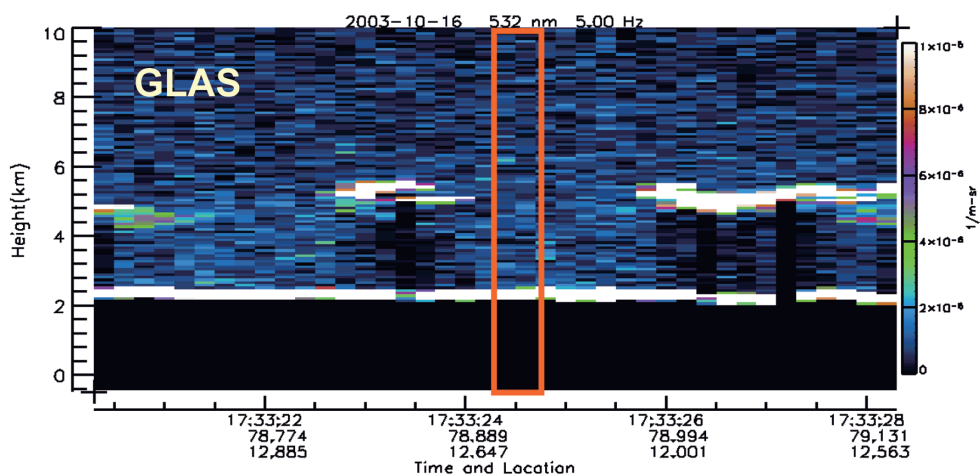

Fig. 8. *The height-time color map of attenuated backscatter cross section at 0.532 μm mea-*
sured by GLAS during the overpass flight above Ny-Ålesund on 16 October 2003. The
orange rectangle corresponds to the averaged profile in Fig. 9 to compare with the MPL
profile for ground validation.

backscatter coefficient. Thus, the cloud top and bottom heights detected by MPL and GLAS
are not consistent as shown in Fig. 9. More precisely stated, the cloud bottom height appar-
ent in GLAS data was higher than that of the MPL because GLAS could not sample the
bottom. Similarly the MPL-detected cloud top height was lower than GLAS because MPL
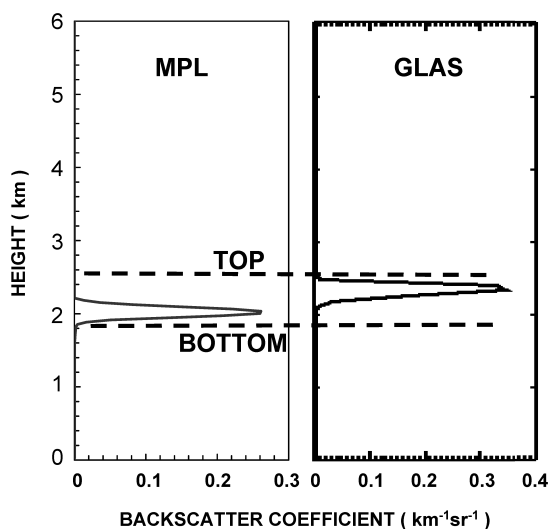could not sample the actual top. The discrepancy of estimated heights is about 300 m

Fig. 9. Vertical profiles of backscatter coefficient obtained from MPL (left) and attenuated backscatter coefficient from GLAS (right), respectively, on 16 October 2003 for an example of the geometrically thin but optically thick case. Expected top and bottom cloud heights are indicated by dashed lines.

between top and bottom, though the presence of the glaciated elements below the cloud base causes some ambiguity here in distinguishing the true cloud base. As a result the COD from MPL is likely underestimated. The retrieved COD near 1.0 must be incorrect. On the other hand, the GLAS retrieval algorithm does not calculate the optical depth when the laser penetration is not confirmed by a diagnosis procedure of detection of a lower cloud or the surface. In general, the lidar technique is limited to COD lower than 3 even for instruments featuring powerful lasers, though GLAS performance is designed to measure COD lower than 2, as mentioned earlier. Optically thick liquid water clouds at low altitudes are not sufficiently penetrated by lidars. This is a known performance limitation of lidar measurements.

4. Summary and conclusions

We summarize the results and discussion in this paper as follows:
1) Micro-Pulse Lidar measurements were performed at Ny-Ålesund, Svalbard in the Arctic to conduct ground validation of the ICESat/GLAS cloud and aerosol measurements.
2) Simultaneous measurements of cloud and aerosol from the ground-based MPL and the space-borne GLAS were successfully obtained for six overpasses above Ny-Ålesund, Svalbard during the ICESat overpass experiment in the Arctic in 2003. Two cases are discussed here.
3) For geometrically thick but optically thin high cloud observed on 2 November 2003, the tops and bottoms of clouds were successfully detected by both MPL and GLAS. The backscatter profiles from both measurements showed fine structure from the same cloud layer. Retrieved cloud optical depth values were in disagreement from the instruments,

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but as a validation of the GLAS algorithm for attenuating cloud layers the results were positive. Since the MPL has a very small field-of-view, there is almost no increase in effective transmission from forward scattering, which is a large factor for space lidar. Consequently it is much more likely that the COD and attenuation correction of the MPL data through thick cloud layers are in error.

4) For geometrically thin but optically thick low cloud observed on 16 October 2003, instrument lasers did not penetrate the cloud. As a result, the cloud optical depths from the MPL were underestimated and not possible from the GLAS data. The satellite-based profile did extend deeper into the layer, as expected from the forward scattering effect.

As a conclusion, the overpass experiment was successful for ground validation of the ICESat/GLAS atmospheric measurements to compare the top and bottom heights, internal structure, and optical depth of thin clouds. In particular, it is confirmed that the ICESat/GLAS exhibited good performance for thin cloud measurements. However, there still exists a necessity of further analyses for clouds and aerosol properties. For instance, more effort to validate the vertical profiles of cloud/aerosol optical parameters such as the backscatter coefficient, extinction coefficient, and S-ratio must be considered. Multiple scattering effects could be further analyzed especially for cloud, snow and ice fog conditions in the polar regions. Comparisons at other MPL sites to GLAS data are under way.

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO; Winker *et al.*, 2002) satellite was launched in April 2006. CALIPSO includes an active lidar instrument for atmospheric measurements that is similar to ICESat/GLAS. MPLNET is involved in the CALIPSO validation/calibration program. As one of the MPLNET sites, the Arctic MPL at Ny-Ålesund is expected to contribute ground validation data for CALIPSO space lidar measurement as well.

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